National and International Disposal Requirements and Guidelines Applicable to GPS

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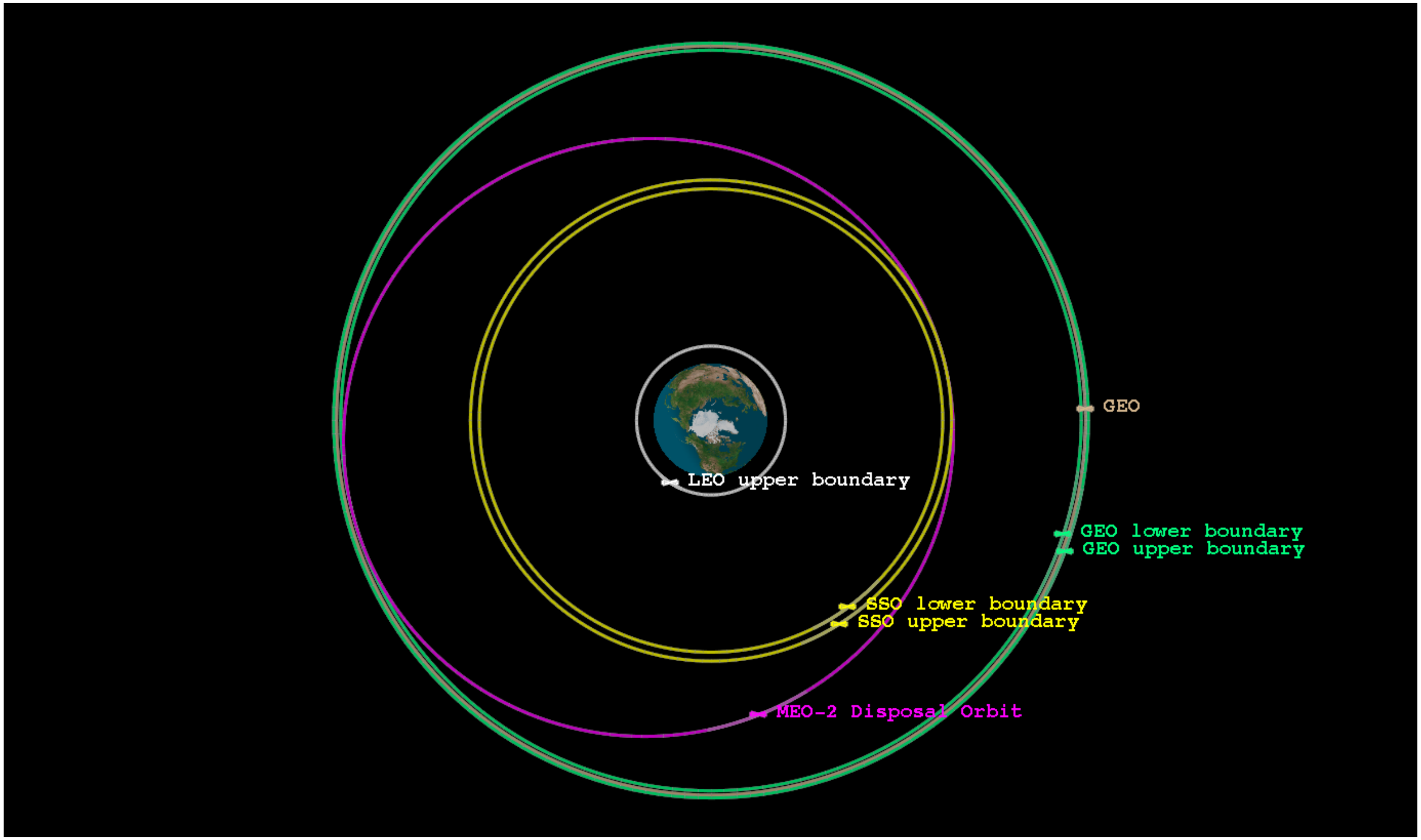
Background

- End-of-life disposal of GPS satellites and rocket body components is addressed by several U.S. and international documents
  - *U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP)*
  - *Air Force Instruction (AFI) 91-217*
  - *Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines*
  - *United Nations Space Debris Mitigation Guidelines*
    - Based on IADC Guidelines but have less detailed guidance
- This presentation summarizes the combined restrictions on disposal orbits from these documents
  - *Where there is lack of clarity in document language, the goal is to extract the most likely interpretation from a technical perspective and from co-author participation in IADC activities*
  - *Other disposal requirements and guidelines (e.g., disposal reliability, passivation, etc.) are not discussed*
  - *More detailed discussion can be found in an Aerospace report (Ref. 1)*

U.S. Government Standards

- U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP)
  - *Requirements applicable to U.S. government missions*
  - *Defines three disposal options (regardless of mission orbit type); atmospheric reentry, storage disposal orbits, and retrieval*
    - Storage disposal orbits may not cross LEO, GEO (shell), and semi-synchronous orbit (SSO, where GPS operates)
    - Decaying disposal orbits with lifetime < 25 years are permitted to cross these regions
- Department of Defense Instruction (DoDI) 3100.12
  - *Requirements applicable to DoD missions*
  - *Same disposal orbit options as in ODMSP*
- Air Force Instruction (AFI) 91-217 (Space Safety)
  - *Requirements applicable to U.S. Air Force missions*
  - *Cites the ODMSP for disposal options*
  - *Has additional restrictions (e.g., collision probability threshold on LEO-crossing orbits)*

Example Compliant Storage Disposal Orbit



Example MEO-2 disposal orbit: 35300 x 20700 km
(all values are altitudes)

IADC Guidelines

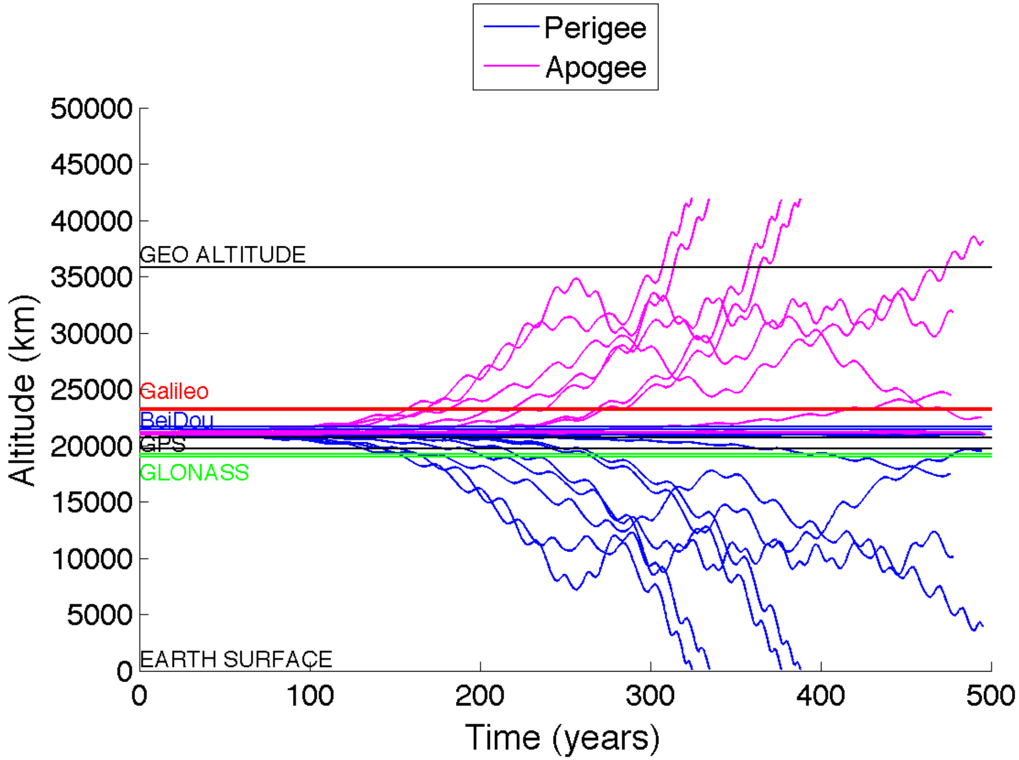
- The IADC is an international governmental forum for the world-wide coordination of activities related to the issue of orbital debris
  - *Comprises 13 member space agencies, including NASA, ESA, JAXA, ROSCOSMOS, and CNSA*
  - *Co-author of this presentation Marlon Sorge is on the NASA delegation*
  - *The IADC Space Debris Mitigation Guidelines promote practices that limit growth of the space debris population; compliance is voluntary*
- Explicitly define protected regions
  - *LEO protected region same as in the ODMSP*
  - *GEO protected region is a torus instead of a shell*
  - *No explicit protected regions in MEO*
- Disposal options are associated with mission orbit type

Combined Disposal Orbit Restrictions for GPS (1)

1. (ODMSP) Storage disposal orbits may not initially cross the LEO, SSO, or GEO protected regions
   - *Only temporarily achievable due to eccentricity growth of disposal orbits; see next slide*

Eccentricity Growth of GPS Disposal Orbits

- Plot shows evolution of disposal orbit apogee and perigee altitudes over 500 years from a recent Aerospace analysis for all 12 GPS IIF satellites
- In four cases, perigee crosses into low Earth orbit (LEO, altitude < 2000 km) and reentry occurs between 300 and 400 years
- In four other cases, the disposal orbit eccentricity grows significantly (perigee crosses the GPS constellation) but perigee does not reach LEO within 500 years
- In the remaining four cases, the disposal orbit is very stable (perigee remains above GPS constellation)

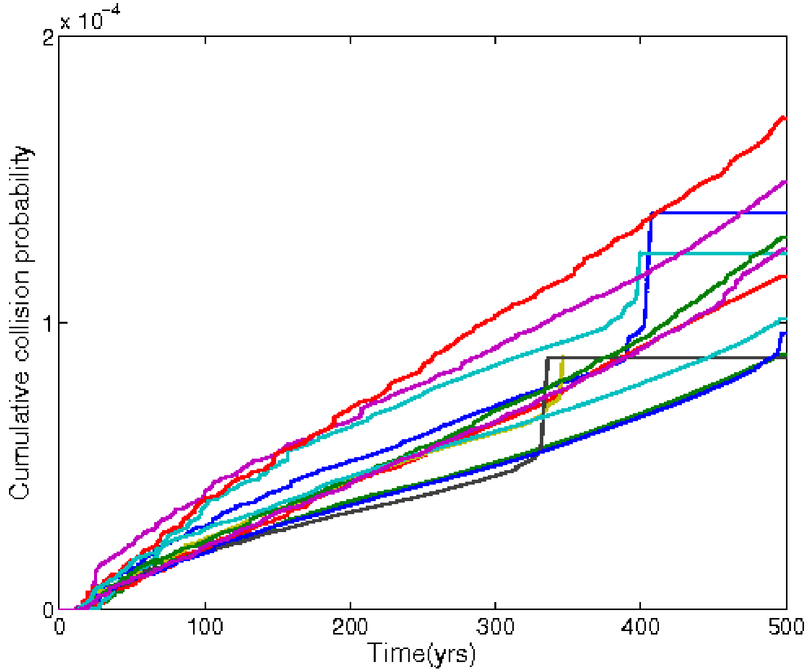


Combined Disposal Orbit Restrictions for GPS (2)

2. (AFI 91-217) Disposal orbits that pass through LEO shall limit collision probability over orbital lifetime with objects larger than 10 cm to be less than 0.001
   - *Adopted from NASA Standard 8719.14A*
   - *Applicable to GPS due to eccentricity growth (disposal orbits can eventually reach LEO)*
   - *Only verifiable for limited time periods (e.g., 200-500 years)*
   - *Assessment requires a future orbital population model*
   - *Demonstrated over 500 years during GPS IIF study using the ADEPT model (described in Ref. 3); see next slide*

Collision Probability After Disposal

- Plot shows the cumulative collision probability vs. time posed to each of 12 GPS IIF SVs by objects in a future population model (FLM, from ADEPT, Ref. 3, includes MEO constellations) after disposal
- For reentry cases, the cumulative collision probability curve ramps up faster when perigee enters LEO (due to higher orbital population density) and then becomes horizontally flat after reentry occurs
- Maximum collision probability over 500 years is 1.72×10^{-4} (very stable orbit)
- Maximum collision probability over 500 years for a reentry case is 1.38×10^{-4}
  - *Less than the 0.001 threshold for LEO-crossing objects in AFI 91-217*
- Minimum over 500 years is 8.77×10^{-5} (a reentry case)



Cumulative collision probability curves become horizontally flat after re-entry

Combined Disposal Orbit Restrictions for GPS (3)

3. Human casualty risk posed by reentering debris
   - *Due to eccentricity growth, some GPS satellites can eventually reenter and pose a human casualty risk*
   - *The ODMSP and AFI 91-217 state that spacecraft and upper stages that reenter shall have human casualty expectation (E_C) < 10^{-4}*
   - *The IADC Guidelines state that reentering debris should not pose an undue risk to people or property*
   - *GPS satellites use the storage disposal orbit option in ODMSP and AFI 91-217, which do not explicitly include the E_C requirement*
   - *Hence this risk is not clearly addressed at the current time*

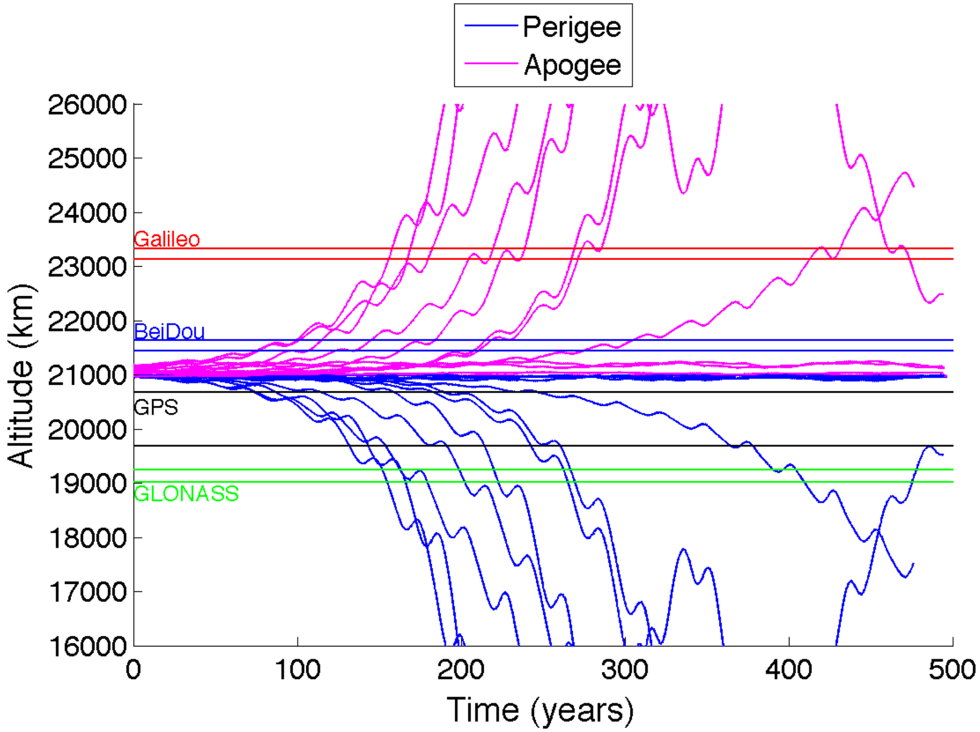
Combined Disposal Orbit Restrictions for GPS (4)

4. (IADC Guidelines) Spacecraft or rocket bodies terminating their operational phases in MEO navigation satellite orbits should be
   - *Maneuvered to reduce orbital lifetime, commensurate with LEO lifetime limitations (25 years)*
     - E.g., upper stages
   - *Or relocated (in a storage disposal orbit) if they cause interference with highly utilized orbit regions*

- "Highly utilized orbit regions" include
  - *LEO and GEO protected regions*
  - *MEO constellations*
    - GPS, Galileo, GLONASS, BeiDou-M, possibly O3b
- Interference, interpreted here as collision risk, cannot be completely avoided due to eccentricity growth
  - *GPS IIF study computed collision probability over 500 years as a metric of interference; see slide 9*
  - *Could be compared with an accepted threshold (e.g., 0.001 from AFI 91-217 and NASA Standard 8719.14A)*

Eccentricity Growth of GPS Disposal Orbits
MEO closeup

- Plot shows evolution of disposal orbit apogee and perigee altitudes over 500 years for all 12 GPS IIF satellites; y-axis near the MEO constellations is magnified
- Interference (collision risk) with MEO constellation orbit regions is unavoidable but may be limited, depending on disposal orbit
  - *For example, collision probability over 500 years for each of the 12 GPS IIF satellites was less than 0.001 (see slide 9)*



Combined Disposal Orbit Restrictions for GPS (5-6)

5. (IADC Guidelines) Disposal orbits that eventually pass through LEO should have lifetime commensurate with 25 years
   - *From text on orbits that have the potential to interfere with LEO*
     - Applicable to GPS due to eccentricity growth
   - *Feasible if the 25-year limit applies only to the time period when the orbit is passing through LEO*
     - Demonstrated over 500 years during GPS IIF study; see slide 7
6. (IADC Guidelines, from practice for GTOs) Disposal orbits that eventually pass through GEO due to eccentricity growth should have apogee above GEO-500 km for not more than 25 years
   - *Applicable to GPS due to eccentricity growth*
   - *Feasibility has not yet been clearly demonstrated*

Study in Progress for SMC/EN in Support of IADC

- A study is in progress by Aerospace for SMC/EN that will determine the effect of different MEO disposal options on the future MEO debris environment
- Will include comparison of two strategies
  - *Delaying eccentricity growth (current GPS practice)*
  - *Accelerating eccentricity growth*
    - Disposal orbits cross constellations sooner, but rate of collisions in graveyard region (hence sub-trackable debris) is reduced (Ref. 4-6)
- SMC/EN is planning to present results to the IADC for discussion regarding future recommended disposal practices

Conclusions

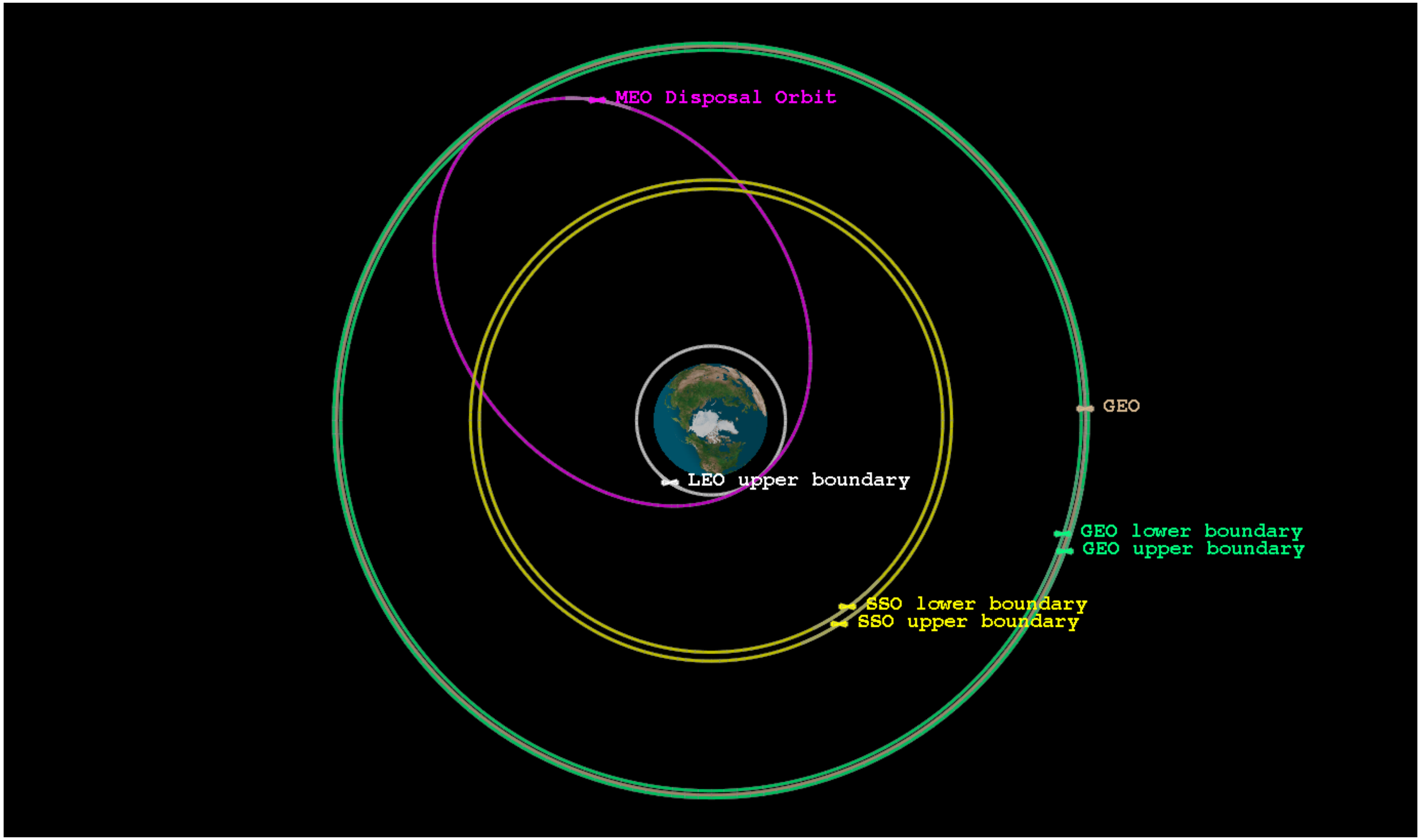
- Combined disposal orbit restrictions for GPS according to U.S. government standards and IADC Guidelines have been summarized
  - *Disposal orbit eccentricity growth determines some of the applicable restrictions*
- A recent study for GPS IIF satellites by Aerospace addresses most of the U.S. requirements and some of the IADC Guidelines
- A study of the effect of different MEO disposal options is in progress

References

1. Jenkin, A.B., Sorge, M.E., “National and International Disposal Requirements and Guidelines Applicable to GPS,” Aerospace report No. TOR-2015-02934, June 18, 2015 (publicly released).
2. Jenkin, A.B., Yoo, B.B., McVey, J.P., Sorge, M.E., Peterson, G.E., “Effect of the Semi-Synchronous Orbit Protected Region on the MEO Debris Environment,” Paper No. AIAA-2014-4229, AIAA/AAS Astrodynamics Specialists Conference, San Diego, CA, August 4-7, 2014.
3. Jenkin, A.B., Sorge, M.E., Peterson, G.E., McVey, J.P., “Recent Enhancements to ADEPT and Sample Debris Environment Projections,” Paper No. IAC-15.A6.2.2, 66th International Astronautical Congress, Jerusalem, Israel, October 12-16, 2015.
4. Jenkin, A.B., Gick, R.A., “Dilution of Disposal Orbit Collision Risk for the Medium Earth Orbit Constellations,” Proceedings of the Fourth European Conference on Space Debris, SP-587, ESA, edited by D. Danesy, ESA Publications Division, Noordwijk, The Netherlands, August 2005, pp. 309-314.
5. Jenkin, A.B., McVey, J.P., ‘Constellation and “Graveyard” Collision Risk for Several MEO Disposal Strategies,’ Proceedings of the Fifth European Conference on Space Debris, Darmstadt, Germany, March 30-April 2, 2009 (ESA SP-672, July 2009).
6. Rossi, A., Anselmo, L., Pardini, C., Jehn, R., “Effectiveness of the De-Orbiting Practices in the MEO Region,” Proceedings of the Fifth European Conference on Space Debris, March 30-April 2, 2009, (ESA SP 672, July 2009).

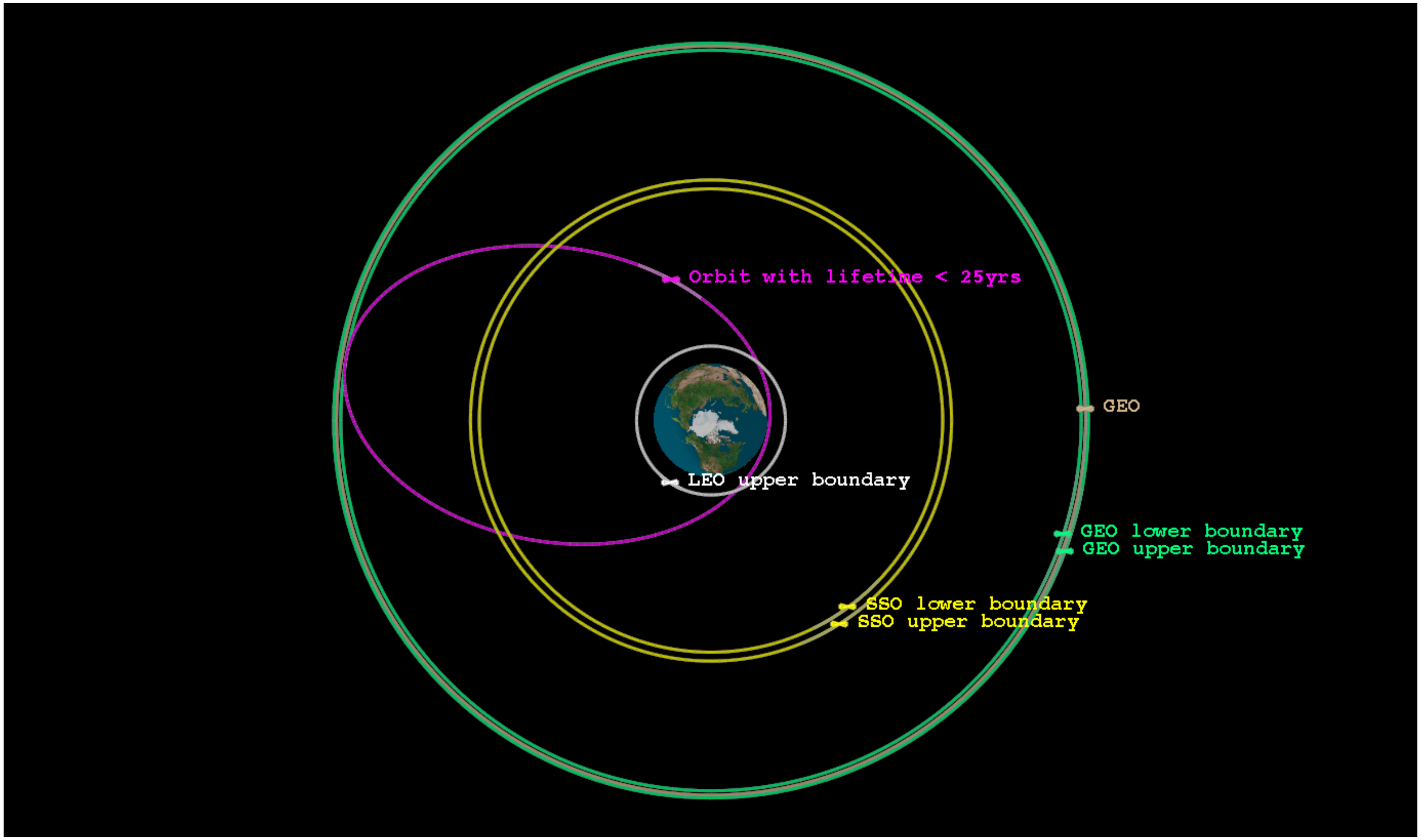
BACKUPS

Example SSO-Crossing Storage Disposal Orbit (Non-Compliant)



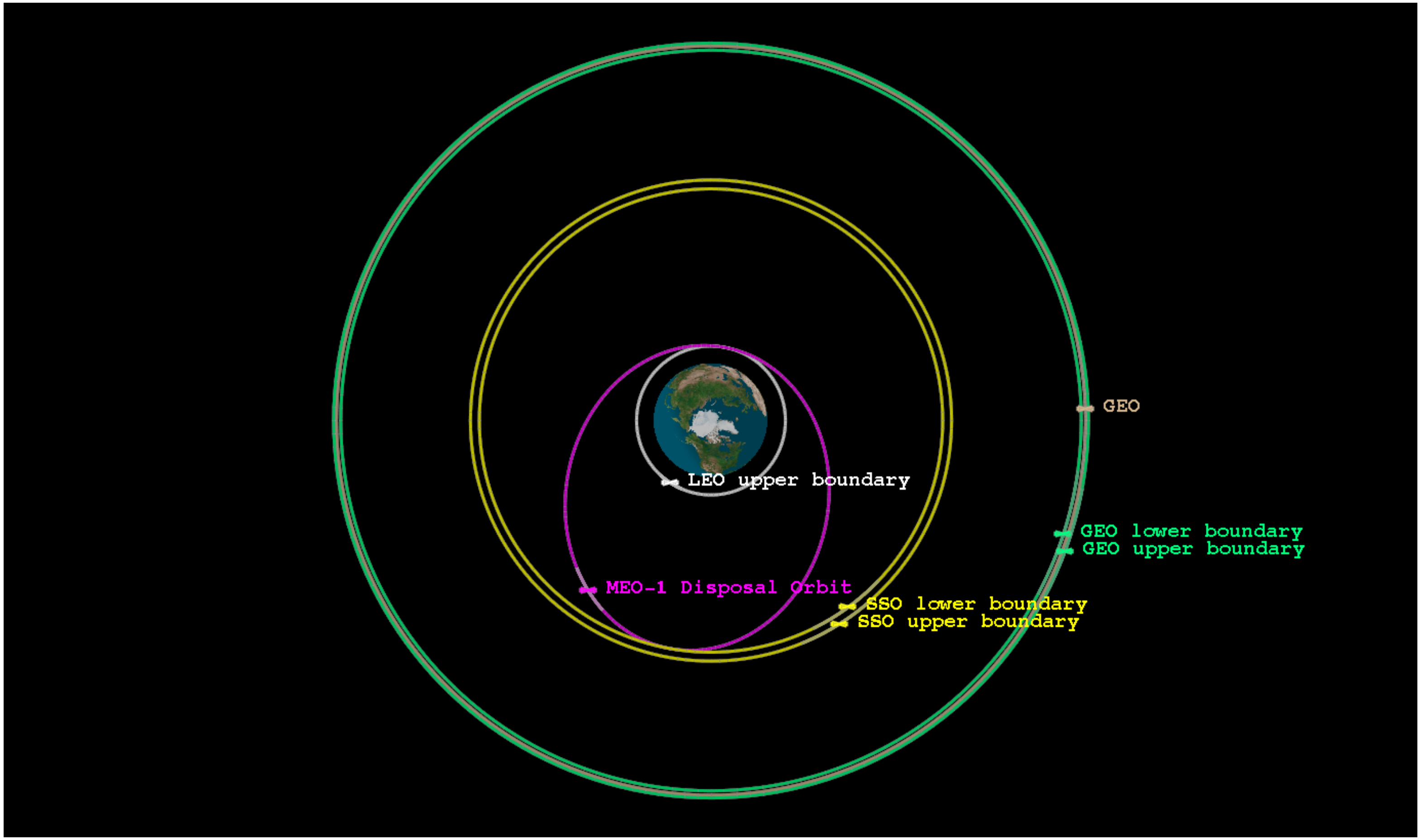
Example MEO disposal orbit: 35300 x 2000 km (SSO crossing)
(all values are altitudes)

Example Disposal Orbit with Lifetime < 25 years (Compliant)



Example disposal orbit: 35300 x 200 km (crossing SSO is permitted if lifetime < 25 years)
(all values are altitudes)

Compliant Storage Disposal Orbit: Example 2

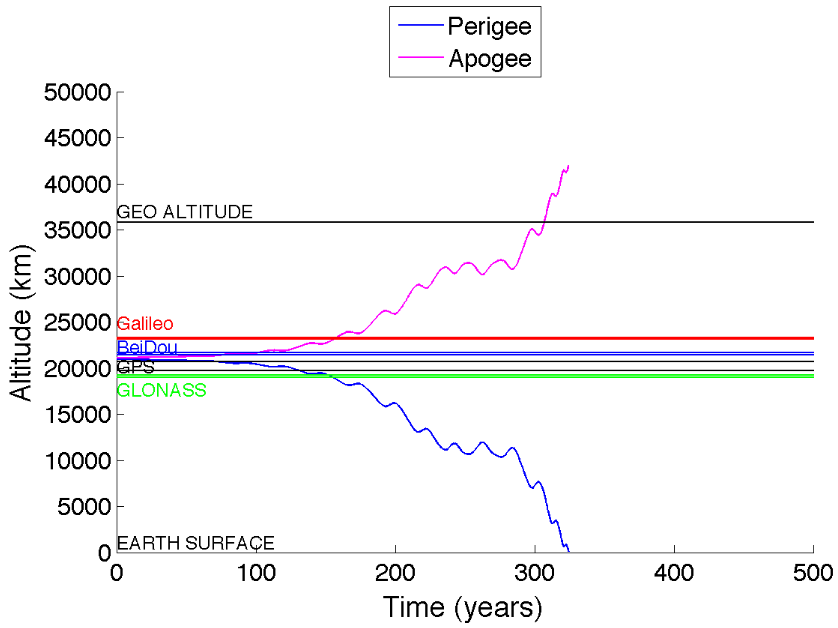


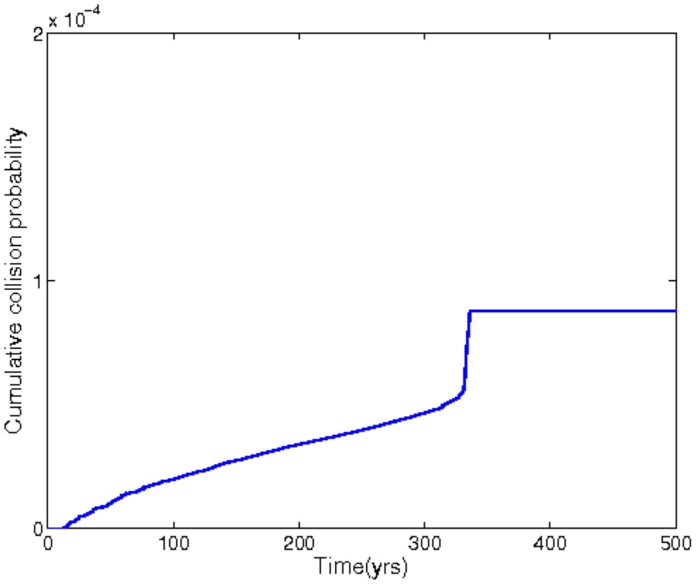
Example MEO-1 disposal orbit: 19700 x 2000 km
(all values are altitudes)

Collision Probability After Disposal

Collision risk with FLM population; Case with lowest collision probability

- Case with lowest collision probability over 500 years (8.77×10^{-5}) is a reentry case
- Collision risk is gone after reentry



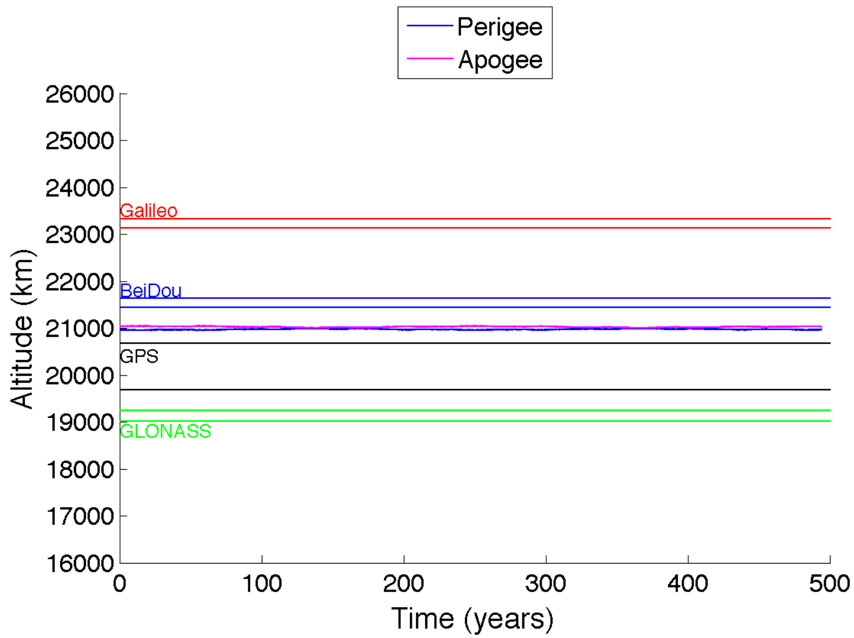


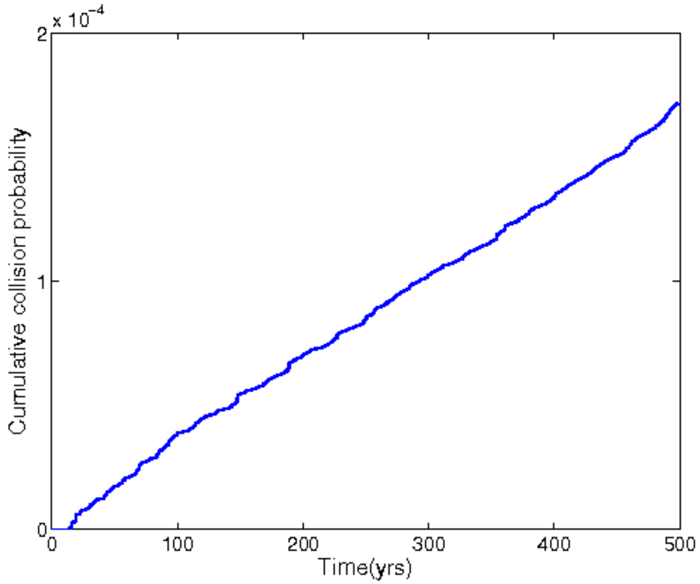
Cumulative collision probability curves become horizontally flat after re-entry

Collision Probability After Disposal

Collision risk with FLM population; Case with highest collision probability

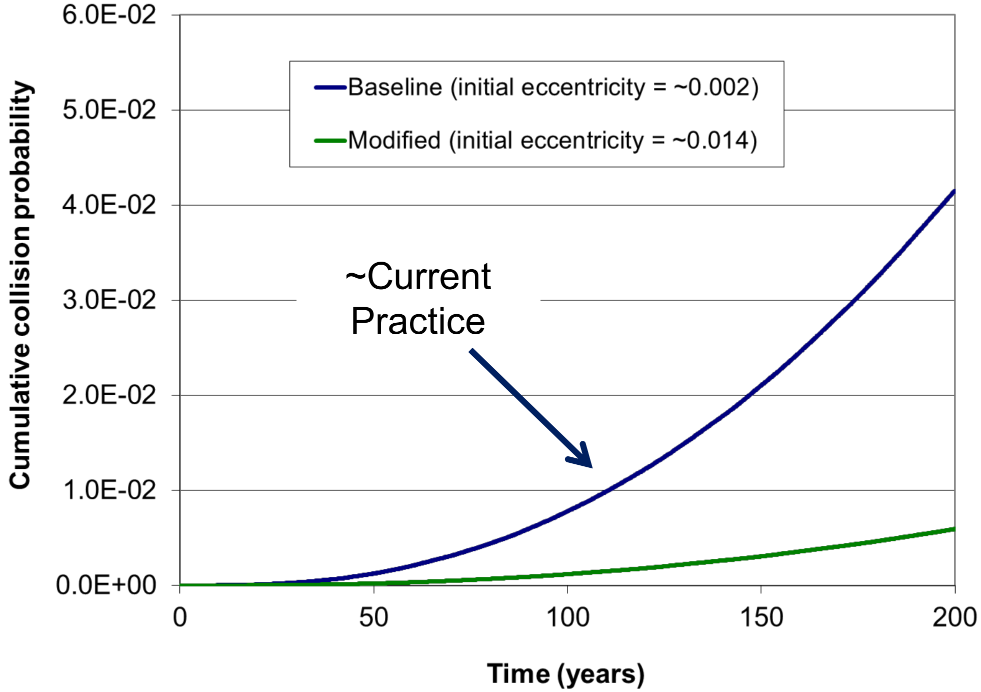
- Case with highest collision probability over 500 years (1.72×10^{-4}) is a very stable orbit case
  - *The SV remains near other accumulating GPS disposed satellites*
  - *Collision risk is highest when GPS disposed satellites minimize eccentricity growth*
- Collision risk will continue to grow after 500 years





Example of Reducing Collision Risk by Using Eccentricity Growth

- This plot shows the cumulative probability of collision between future disposed GPS satellites for two disposal orbit strategies (from study of Ref. 5)
  - *Baseline (eccentricity is minimized, representative of current practice)*
  - *Modified: Initial eccentricity is set to ~0.014 to increase eccentricity growth*
- Increasing eccentricity growth results in dilution of collision risk due to spreading of apogee and perigee



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